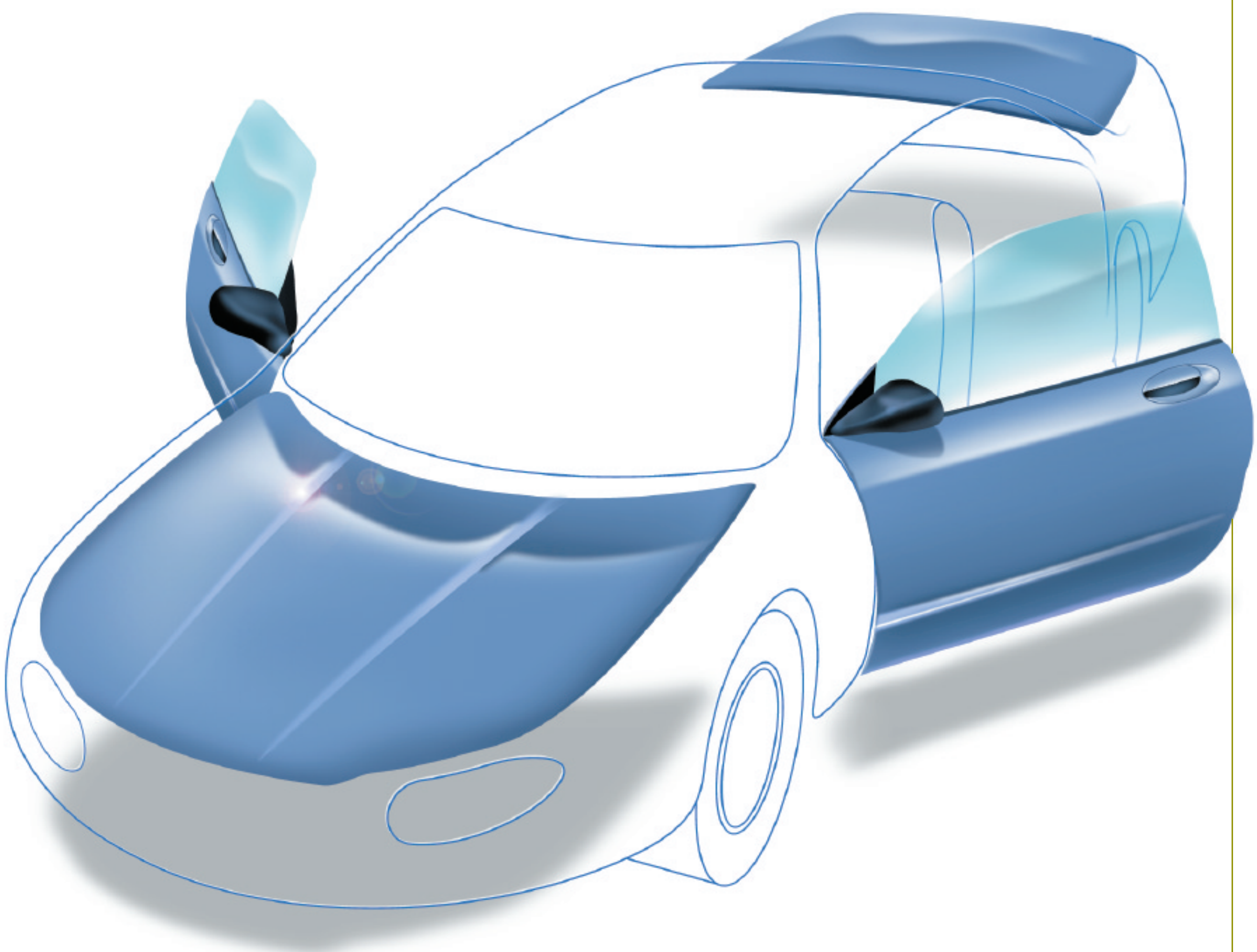
ULTRALIGHT STEEL AUTO CLOSURES



Overview Report

May 2001

An overview of the design, materials, manufacturing, structural performance and economic analysis of the UltraLight Steel Auto Closures (ULSAC) Program

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ULSAC Program Highlights

In May 2000, the UltraLight Steel Auto Closure (ULSAC) Consortium unveiled a lightweight frameless steel door design that achieves 42 percent weight savings over the average benchmarked* frameless door and 22 percent savings over the lightest benchmark, a framed door. ULSAC was commissioned by this international consortium of 31 sheet steel producers to assist their automotive customers with viable lightweighting steel solutions. The ULSAC design and engineering team, Porsche Engineering Services, Inc. (PES), Troy, Michigan USA, accomplished this significant weight savings by using high and ultra high strength steels, combined with technologies such as tailored blanks and hydroforming. The door outer panel of this first round of demonstration hardware is made of stamped 0.7 mm Bake Hardenable (BH) 260 sheet steel.

During the design and development of the ULSAC frameless door, the ULSAC Consortium evaluated further mass reduction, using sheet hydroforming for the door outer. Consequently, the ULSAC Validation Phase continued beyond May 2000 with sheet hydroforming process development for the door outer as a means to compile practical research documentation for this developmental process with mass reduction potential. Door structures were successfully manufactured with 0.6 mm Dual Phase (DP) 600 hydroformed steel outer panels achieving additional weight savings.

ULSAC DOOR RESULTS

with Stamped Outer
0.7 mm BH 260 Steel
Normalized Mass: 13.27 kg/m^2
Total Mass: 10.47 kg

- 42% lighter than the average benchmarked frameless door
- 22% lighter than the best-in-class benchmarked door (framed door)

with Sheet Hydroformed Outer
0.6 mm DP 600 Steel
Normalized Mass: 12.38 kg/m^2
Total Mass: 9.77 kg

- 46% lighter than the average benchmarked frameless door
- 27% lighter than the best-in-class benchmarked door (framed door)

BOTH DOORS FEATURE:

- Unique tubular frame structure
- High and ultra-high strength steels, tailored blanks and tube hydroforming
- State-of-the-art structural performance
- Reduced mass with no compromise to safety
- Affordable high volume manufacture

* *ULSAC concept phase benchmarking used 1997 model year vehicles. Since that time, some lighter-weight doors have been developed.*

1 Executive Summary

1.1 Background

The UltraLight Steel Auto Closure (ULSAC) program demonstrates the effective use of steel in producing lightweight, structurally sound automotive closure panels that are manufacturable in high volume and affordable. ULSAC began as a concept development program, producing innovative concept designs for doors, hoods, decklids and hatches that are up to 32 percent lighter than benchmarked averages and 10 percent lighter than best-in-class, while meeting stringent structural performance targets.

These results were obtained through innovative steel design combining ultra-high strength steels with manufacturing technologies such as tailored blanks, hydroforming and laser welding.

Like the UltraLight Steel Auto Body (ULSAB) study, the ULSAC program was commissioned by an international consortium of 31 sheet steel producers to assist their automotive customers with viable lightweighting solutions. The ULSAC Consortium contracted Porsche Engineering Services, Inc. (PES), Troy, Michigan USA, to provide design and engineering management for both the Concept and Validation Phases of the program.

1.2 Validation Phase – Door with Stamped Outer

Following the successful Concept Phase, the ULSAC program proceeded to the validation of a frameless door design. The ULSAC Consortium chose to build and test the frameless door as a demonstration because it is representative of a range of closure concepts developed during the Concept Phase. The frameless door embodies most of the advanced concepts in structure, technology and steel usage developed in the Concept Phase designs and demonstrates their feasibility. Successful manufacture of the frameless door dramatically demonstrates the value and structural efficiency in combining innovative design, advanced technology and steel.

In May 2000, the ULSAC Consortium released the Validation Phase results for a complete frameless door structure. The door structure featured a high and ultra high strength steel tubular frame and a stamped outer panel of 0.7 mm BH 260 steel. The complete door structure weighed 10.47 kg (normalized mass, 13.27 kg/m^2). This is 22 percent lighter than the framed door best-in-class benchmark and 42 percent lighter than the average frameless door Validation Phase benchmark. This was achieved without compromising safety or structural performance and at no cost penalty.

1.3 Validation Phase – Door with Sheet Hydroformed Outer

Additional mass reduction also was investigated in the Validation Phase by manufacturing the outer panel, using the sheet hydroforming process. The process was intended to gain uniform stretch in the middle of the panel while maintaining dent resistance and oil canning performance at a lower mass.

Sheet hydroforming for complex parts, such as door outer panels, is a process under development. With completion of the Validation Phase, much more has been learned about the performance of differing grades and thicknesses and how stamping and hydroforming compare in dent resistance and oil canning, as well as overall door performance and cost, for the ULSAC door design.

A similar range of materials utilized for the manufacture of the stamped outer panels was used for the production of the test doors with sheet hydroformed door outer panels.

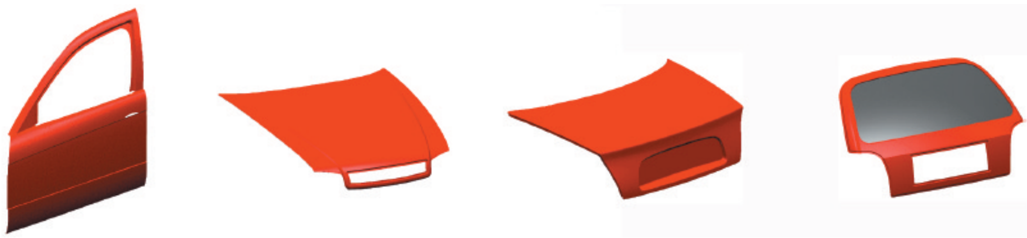
Oil canning and dent testing determined that 0.6 mm thick Dual Phase (DP) 600 steel material was the best choice among the sheet hydroformed outer panels to use in the demonstration hardware (DH) door structure. The validation door with a sheet hydroformed outer panel weighs 9.77 kg and meets all structural performance and safety targets at a slight cost increase of $3.72 per door, assuming an annual vehicle production volume of 225,000. With the 0.7 kg further reduction in weight, this door is 27 percent lighter than the best-in-class benchmarked door and 46 percent lighter than the average frameless door benchmark.

This research was conducted to explore the potential of the sheet hydroforming process for further mass reduction in auto body outer panels. The results indicate that, with further development to reduce cycle times, a sheet hydroformed outer panel could be used to effect additional weight reduction over the already significant achievement of the ULSAC door with stamped outer panels.

1.4 Information In This Overview Report

This overview report contains the May 2000 results for doors using stamped outer panels and full details on the manufacture of the complete door structure. This report also contains a summary of the results from the manufacture of outer panels using the sheet hydroforming process. April 2000 and January 2001 ULSAC Engineering Reports are available on CD-ROM and on the web at www.ulsac.org. These reports contain comprehensive details on the design, manufacture and results of the ULSAC program.

2 Concept Phase



2.1 Approach

The ULSAC Concept Phase encompassed benchmarking, target setting and conceptual design, which includes FEA calculation and cost analysis. Benchmarking was performed to define current state-of-the-art closures; target setting provided specific objectives; and conceptual design was undertaken to demonstrate ideas that would meet the targets and generate data to support the concepts.

2.2 Benchmarking

In the Concept Phase, PES benchmarked closures from eighteen 1997 model vehicles. The benchmark vehicles were chosen to provide evaluations of specific closures. For the door these included roof integrated, frame integrated and frameless. Hood design concepts included conventional and grill integrated. The decklid design was the conventional with a tail, and the hatch design was the lift gate type.

The benchmark study established mass (without glass), dimension and structural performance standards for doors, hoods, decklids and hatchbacks. PES normalized this data to make accurate comparisons among the closures and then evaluated designs and components of the benchmarked closures. The data was normalized by dividing the total mass of a closure by its true surface area to get a kilograms per square meter (kg/m^2) value. This allowed direct comparison of different size closures.

In addition, PES assessed costs associated with manufacturing each of the closures.

From this benchmarking data, PES developed mass and performance targets for the closure designs.

2.3 Target Setting

Targets were set for dimensions, structural performances and mass for doors, hoods, decklids and hatches. Dimensional targets for doors, hoods and decklids were based on ULSAB styling surface dimensions because those dimensions were very close to ULSAC benchmarked averages, and they provided the outer surface data needed to conduct this closure study. For hatch dimensional targets, PES used the measurements from a lift-gate type hatch, which was the lightest and smallest one benchmarked. Structural performance targets were set at the midpoint in the range from a survey of OEM requirements. Mass targets, however, were set at ten percent better than best-in-class of the benchmarked closures.

2.4 Concept Phase Results

The ULSAC Concept Phase produced innovative closure designs that met or exceeded structural targets while significantly reducing mass at little or no cost increase. A Concept Phase Engineering Report, including designs for all closures, FEA analysis and results, cost information and structural performance, is available on CD-ROM from the ULSAC Program Management Office by e-mail request to contact@ulsac.org. A summary is also available at the ULSAC website at www.ulsac.org.

Mass and cost comparison results for each design are given in the Table 1 and 2.

Table 1: **Mass Comparison – Concept Phase Results**

	Benchmark (kg/m^2)		Target (kg/m^2)	ULSAC	
	Range	Average		(kg/m^2)	(kg)
Door – Roof Integrated	17.0 – 23.4	19.7	15.5	15.1	13.2
Door – Frame Integrated				15.5	13.2
Door – Frameless				14.3	11.4
Hood – Conventional*	8.8 – 14.2	11.5	8.0	7.9	13.3
Hood – Grill Integrated*				7.9	13.7
Hood – Conventional**				8.5	14.3
Hood – Grill Integrated**				8.4	14.7
Decklid – Conventional*	8.9 – 16.1	11.2	8.0	8.0	9.8
Decklid – Conventional**				8.6	10.6
Hatch – Tube Hydroformed	12.5 – 15.2	13.9	11.3	10.3	6.7
Hatch – Tailored Blank				10.6	6.9
Hatch – Hydroformed Ring				10.9	7.1
Hatch – Sheet Hydroformed				9.5	6.2

Table 2: **Cost Comparison in US $ – Concept Phase Results**

	Baseline	ULSAC
Door – Roof Integrated	67 Frame Integrated Door	67
Door – Frame Integrated		72
Door – Frameless		65
Hood – Conventional*	40	44
Hood – Grill Integrated*	46	52
Hood – Conventional**	40	40
Hood – Grill Integrated**	46	46
Decklid – Conventional*	31	36
Decklid – Conventional**	31	33
Hatch – Tube Hydroformed	29	36
Hatch – Tailored Blank	29	33

* with steel sandwich material inner panel

** with sheet steel inner panel

Validation Phase

ULSAC proceeded to the validation of a frameless door concept design. In the Validation Phase, the Consortium chose to build and test the frameless door as a demonstration example representative of a range of closure concepts developed in the Concept Phase. The frameless door embodies most of the important advancements in structure, technology and steel usage developed in the Concept Phase designs and is a demonstration of their feasibility. Successful manufacture of the frameless door dramatically demonstrates the value and structural efficiency in combining advanced technology and steel.

3.1 Scope of Validation of Frameless Door Design

The ULSAC Validation Phase includes further optimization of the frameless door design plus preparation and testing of demonstration hardware to illustrate affordable manufacturing feasibility. The program encompasses the following:

- Detail design optimization and CAE analysis of structural performance
- Forming simulation of stamped and hydroformed parts
- Build of door structure assemblies, for testing and demonstration hardware
- Testing for dent resistance and oil canning
- Testing for structural performance
- Validation of forming simulation with strain analysis
- Documentation of manufacturing parameters
- Documentation of material properties
- Documentation of dimensional control data
- Economic analysis to evaluate cost effectiveness

Door structure assemblies were built and tested with stmped outer panels and with sheet hydroformed outers. Stamped outer results are reported in the April 2000 ULSAC Engineering Report. Sheet hydroformed outer results are reported in the January 2001 ULSAC Engineering Report. Both are summarized in this Overview Report.

3.2 Additional Benchmarking

The ULSAC Concept Phase concentrated on benchmarking a mixture of door types without specific focus on frameless doors. Upon selecting the frameless door concept for the ULSAC Validation Phase, additional benchmarking was conducted to better document current state-of-the-art frameless door structures in terms of their mass and structural performance and to have data with which to compare the ULSAC frameless door. Three doors, taken from vehicles currently in production and sold worldwide, were purchased and tested. These doors will be referred to as Doors A, B and C. To ensure comparability of results, all door structures were tested on the same testing devices.

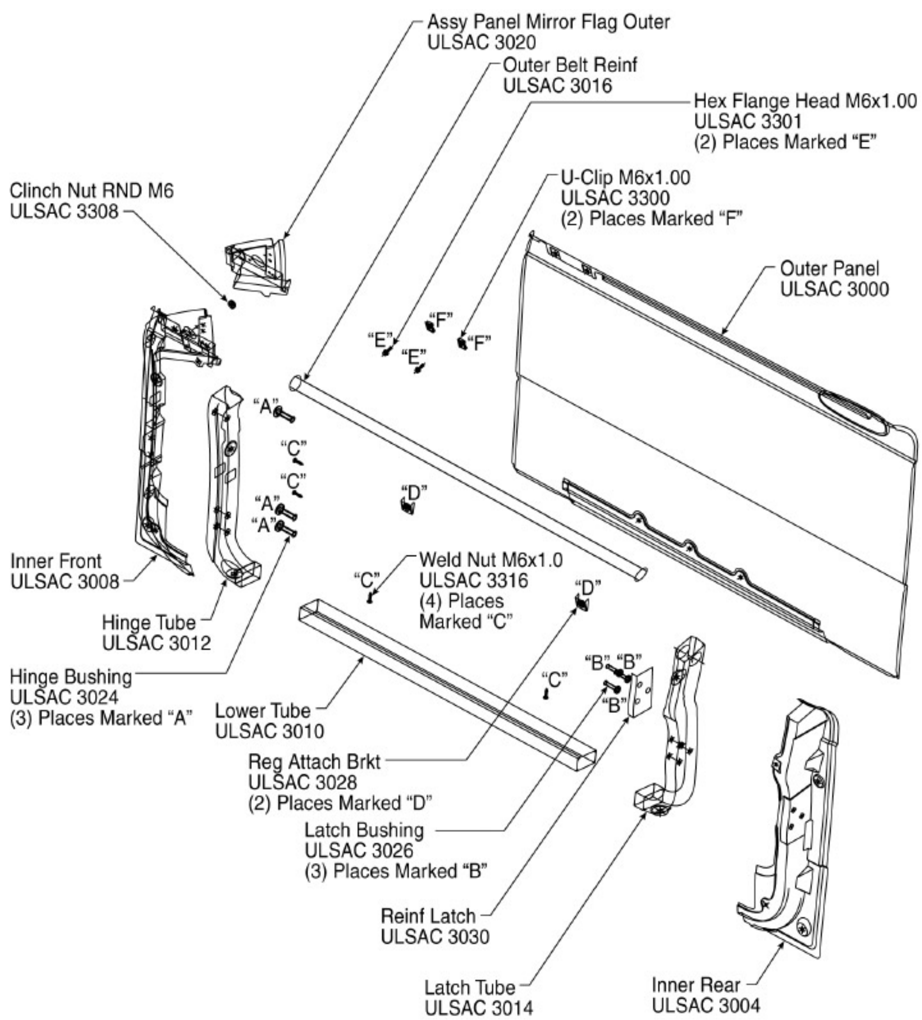
Design and engineering focused on refining of the concept design for manufacturing and assembly, further reducing door structure mass and maintaining structural performance and affordable costs.

4.1 Validation Phase Design

The ULSAC frameless door Validation Phase design is shown in Figure 1. PES detailed each part, continuing an iterative, holistic approach to analyzing the frameless door concept design. Through each iterative step, re-analysis confirmed the effectiveness of the latest optimizations and enabled engineers to reduce mass through consolidation of functions and elimination of redundant components. This resulted in the creation of an efficient, optimized door structure.

Simultaneous engineering, involving suppliers and consortium members, provided feedback regarding material selection, manufacturability and cost, which resulted in design and assembly changes from Concept Phase to Validation Phase as follows:

Figure 1: **Frameless Door Validation Phase**

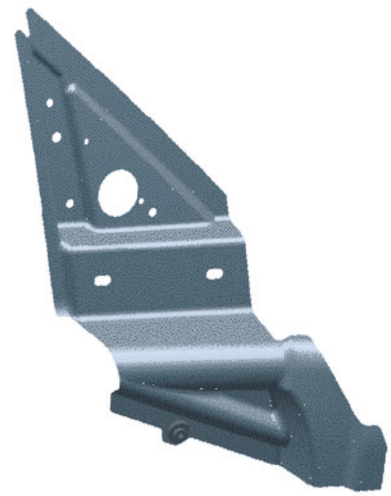


4.1.1 #3020 Mirror Flag Outer

The mirror flag was designed in the Concept Phase as a thin wall casting to integrate the attachment of the mirror, glass run channel and upper hinge into one upper frame node.

According to manufacturers of thin wall steel castings, the part is feasible but not cost efficient for mass production. Changing to iron castings as an alternative resulted in tolerance and joining problems. As a result, in the Validation Phase, two stamped parts were substituted for the cast mirror flag. These two parts form the glass drop channel and capture the outer belt reinforcement to build a strong structural node, which transfers loads to and from the hinge tube. The mirror flag outer, shown in Figure 2, is assembled with a clinch nut for the window regulator module attachment. The mirror flag inner is part of the inner front stamping.

Figure 2: **Mirror Flag Outer**



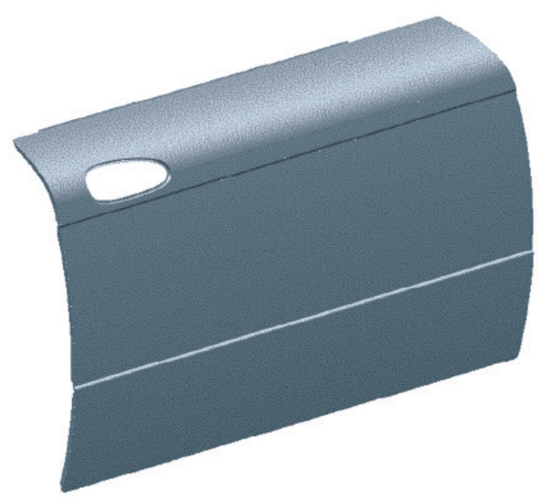
4.1.2 #3000 Door Outer Panel

As in the Concept Phase, the design utilizes the ULSAB styling theme for the door outer panel. In the Concept Phase, the door outer panel used a tailored blank layout to provide additional beltline stiffness and to enhance frontal collision crashworthiness. The redesign of the door structure and the introduction of an ultra high strength steel outer belt reinforcement (detailed in 4.1.3 and 6.1.1) eliminate the need for a tailored blank.

The lower part of the inner panel between the inner front and rear is formed onto the outer panel and folded to the inside. This reduces mass by eliminating the hem flange in this area.

Two manufacturing techniques were used to produce outer panels in BH 210 and 260 and DP600 steels at 0.6 and 0.7 mm thicknesses for test door structures. First, a conventional stamping process was used. After dent and oil canning testing, Bake Hardenable (BH) 260 MPa yield strength steel at 0.7 mm thickness was chosen as the best material to use in the ULSAC stamped outer panel manufacture (see Figure 3).

Figure 3: **Door Outer Panel**

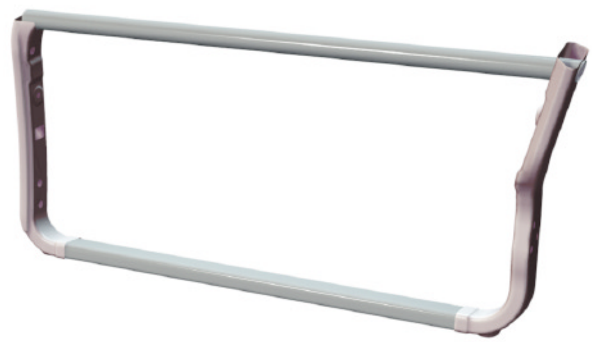


Doors produced with stamped outers achieved a remarkable weight reduction over benchmarked doors. The program continued, however, to explore the potential for additional mass reduction in outer body panels through use of a developmental sheet hydroforming process. Outer panels in a similar range of materials (0.6 and 0.7 mm thicknesses, BH 210, 260 and DP 600) were successfully manufactured using this process in all grades and thicknesses tested. Ultimately, 0.6 mm DP 600 steel performed best in testing procedures and was used to manufacture door structures with sheet hydroformed outers. For information about the sheet hydroforming process, see Section 6.2.3. For testing and economic analysis comparison of both processes, see Sections 9.0 and 10.0.

4.1.3 Door Structure – Frame Design

For the door structure (see Figure 4), the Concept Phase design, which consisted of a one-piece hydroformed lower door-frame and a reinforcement, is modified to utilize two smaller hydroformed parts and a straight rectangular tube part. This reduces tooling cost and, most important, it allows the design engineer to select a precise diameter, material grade and thickness combination for the front hinge tube, the rear latch tube and the front door lower tube, independently of one another and based entirely on functional requirements. This results in a structure with reduced mass.

Figure 4: **Door Structure**



#3014 Latch Tube **–** The hydroformed latch tube (see Figure 5) material thickness was reduced from 1.2 mm to 1.0 mm, at 280 MPa yield strength, compared to the concept design lower doorframe. This reduction in material thickness reduced mass, but made it necessary to add a local reinforcement at the latch area to provide the extra strength needed for side impact intrusion. The latch reinforcement is made from a 1.2 mm 140 MPa yield strength material and laser welded to the latch tube. The lower end of the latch tube is designed to accommodate the front door lower tube. In the frame assembly, the lower tube is slotted into the latch tube and MIG-welded.

Figure 5: **Latch Tube**

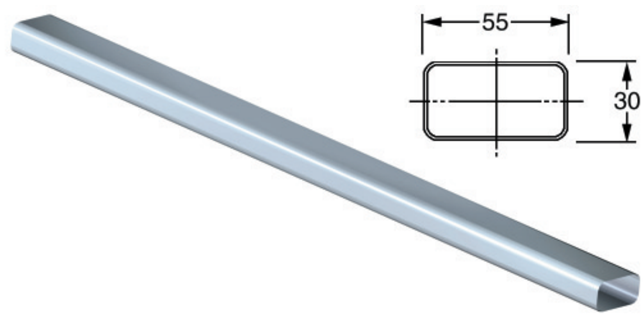
***#3012 Hinge Tube* –** The hydroformed hinge tube (see Figure 6) was part of a redesign of the door structure, but the material thickness was kept at the Concept Phase specification of 1.2 mm with yield strength of 280 MPa. The lower end of the hinge tube was designed to accommodate the front door lower tube, which is slotted into the hinge tube and MIG-welded.

For the attachment of the upper and lower hinges, three bushings are laser welded through to the hinge tube and MIG welded on the inside. The weld-through bushings provide the ability to attach the hinge and function as bulkheads inside the tube. They stabilize the tube section under loads transferred from the hinges.

Figure 6: **Hinge Tube**

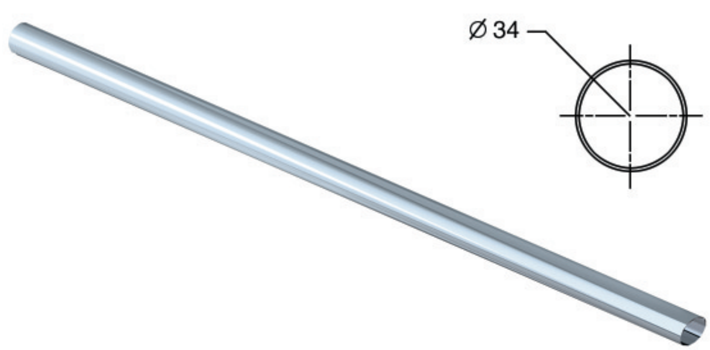
***#3010 Lower Tube* –** The lower tube (see Figure 7) was designed using a straight rectangular ultra high strength steel tube with material thickness of 1.6 mm and a tensile strength of 800 MPa. It replaces the middle section of the Concept Phase design and eliminates the roll-formed impact beam reinforcement, which saves costs for parts manufacturing, tooling and assembly.

Figure 7: **Lower Tube**



***#3016 Outer Belt Reinforcement* –** Redesign of the mirror flag facilitated replacement of a tube hydroformed outer belt reinforcement (1.2 mm thickness/ 350 MPa yield strength), specified in the Concept Phase, with a straight ultra high strength steel tube (1.0 mm thickness/800 MPa tensile strength. See Figure 8).

Figure 8: **Outer Belt Reinforcement**



Further, changing from 1.2 mm material thickness to 1.0 mm reduces mass without sacrificing the structural integrity of the door structure. Using this ultra high strength steel tube also enhances the side impact crush resistance of the door structure by functioning as a second intrusion beam in conjunction with the lower beam. The use of a straight tube instead of a tube hydroformed part reduced part cost and hydroformed tooling costs.

4.1.4 Inner Panels Front and Rear

The inner rear and front panel were redesigned in the Validation Phase to account for the changes made in the mirror flag area and during door structure optimization.

#3008 Inner Front **–** When the mirror flag was redesigned to a two-piece stamped part, the challenge was to consolidate as many functions as possible, which were previously incorporated into the mirror flag design, without adding significant parts. The inner front (see Figure 9) is designed to form the inside of the mirror flag and to provide one half of the cavity in which the outer belt reinforcement is sandwiched together with the mirror flag outer, creating a strong structural node. The part size had to be increased in height and width to incorporate the mirror flag and to account for the attachment of the window regulator module.

Figure 9: **Inner Front**

A tailored blank, with 1.0/1.2 mm material thicknesses/140 MPa yield strength, replaces the need for a lower hinge reinforcement. The increased thickness in the lower portion of the blank is required to achieve acceptable structural performance. The thinner material on the upper portion gives strength to the mirror flag to support the outside rear view mirror and outer panel attachment, but at lower mass.

#3004 Inner Rear – During the optimization process for assembly, the size of the inner rear (see Figure 10) was increased to provide for more welding surface to overlay the latch tube. The inner rear also provides the attachment locations for the door inner panel module.

Figure 10: **Inner Rear**

Table 3: **ULSAC Door Structure Parts List (Actual Mass)**

Part No.	Part Name	Mass (kg)
3000	Door Outer Panel (Stamped)	4.600
3000	Door Outer Panel (Sheet Hydroformed)	3.813
3004	Inner Rear	0.467
3008	Inner Front (TWB)	1.130
3010	Lower Tube	1.438
3012	Hinge Tube	0.653
3014	Latch Tube	0.601
3016	Outer Belt Reinforcement	0.778
3020	Mirror Flag Outer	0.371
3024	Hinge Bushing (3@0.041ea.)	0.132
3026	Latch Bushing (3@0.014ea.)	0.039
3028	Window Regulator Attachment (2@0.007ea.)	0.013
3030	Latch Reinforcement	0.054
3300	U-Clip M6x1.00 (2@0.011 ea.)	0.021
3301	Hex Flange Head M6x15 (2@0.4 ea.)	0.080
3312	Adhesive Bonding - Lower Tube	0.070
3316	Weld Stud M6x16 (4@0.005 ea.)	0.020
	Door Structure (Stamped Outer) Mass Total	**10.467**
	Door Structure (Sheet Hydroformed Outer) Mass Total	**9.68**

4.2 Package

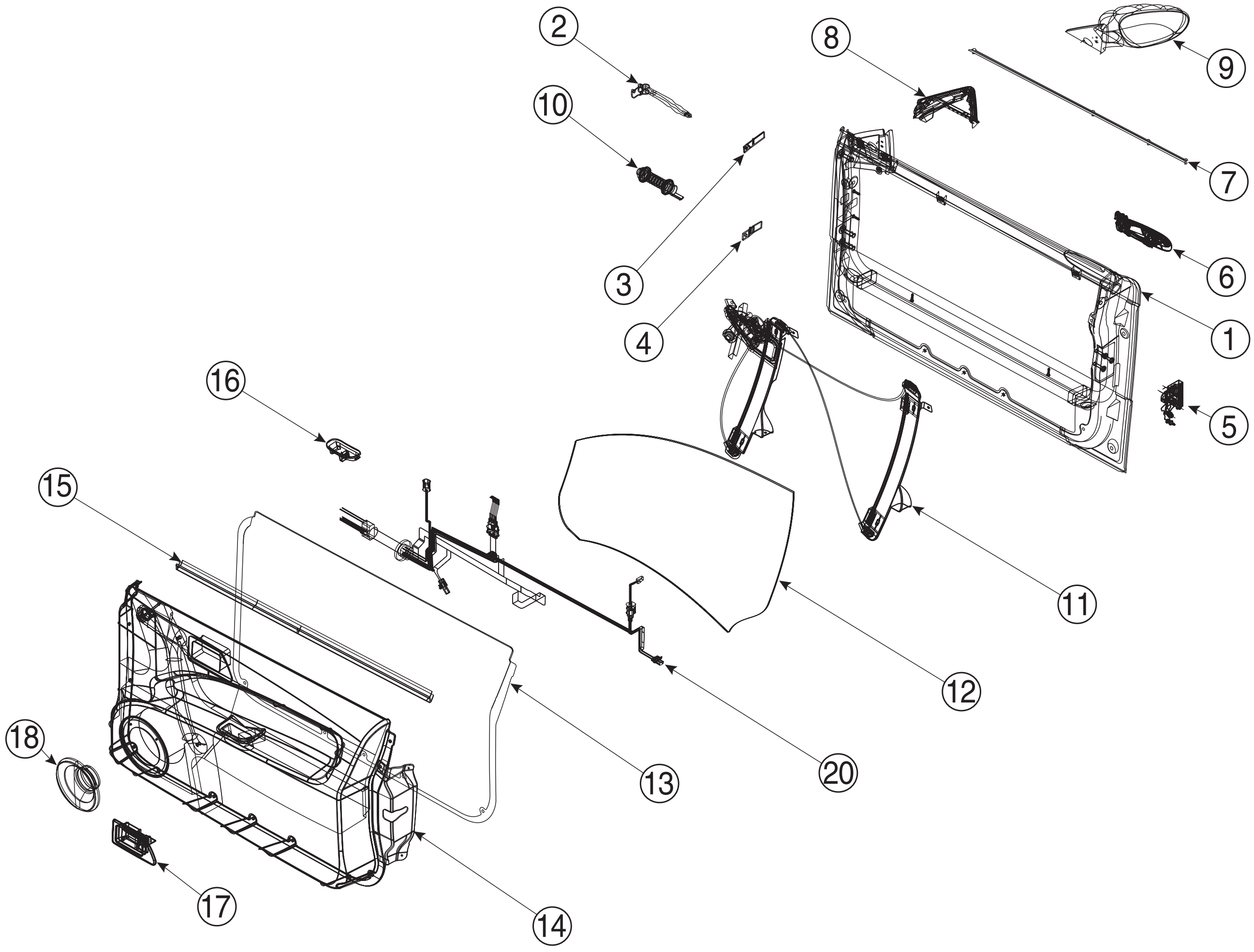
PES took the design beyond the structural components, the main focus of the program, and developed a concept for a complete door component package to ensure the door's total functionality. This approach provides an example of a complete working, lightweight door and investigates the impact of selected components on the final door assembly and assembly sequence.

Prior to component selection, several factors were reviewed, such as component mass and the impact of mass on the door structure part design. PES also reviewed available state-of-the-art technologies, modular design possibilities and suitable assembly processes. An exploded view of the ULSAC door including all package components is shown in Figure 11.

Style, driver safety, comfort and convenience were all considered in choosing components for the door. The complete door features a trim panel-integrated energy absorbing foam block (rather than a separate foam inner as is current practice), electronic door latch and outer handle, power window and lock, and heated, electronic side mirrors.

An overview of the assembly sequence for the complete door can be found in Section 8.2.2.

Figure 11: **Exploded View of ULSAC Door**



Item No.	Part No.	Name
1	3202	Final Assembly Front Door RH
2	3126	Check Strap
3	3158	Bracket Trim Attachment – Upper
4	3156	Bracket Trim Attachment – Lower
5	3100	Latch Assembly
6	3104	Outside Remote Handle
7	3112	Outer Belt Seal
8	3110	Mirror Flag Seal
9	3122	Mirror Assembly
10	3140	Boot Harness

Item No.	Part No.	Name
11	3108	Window Regulator Assembly
12	3102	Glass
13	3146	Vapor Barrier
14	3114	Trim Panel Assembly
15	3124	Inner Belt Seal
16	3136	Switch Assembly
17	3106	Inside Remote Handle
18	3128	Speaker
19	3148	Mirror Flag Cover
20	3138	Wire Harness Assembly

CAE Analysis

CAE analysis was used during the development of the ULSAC frameless door to aid the design optimization process and, specifically, to predict structural performance. This ensured that the actual manufactured door would achieve performance similar as that predicted for the concept door design. The analysis was conducted using the door structure with a 0.7 mm BH260 stamped outer.

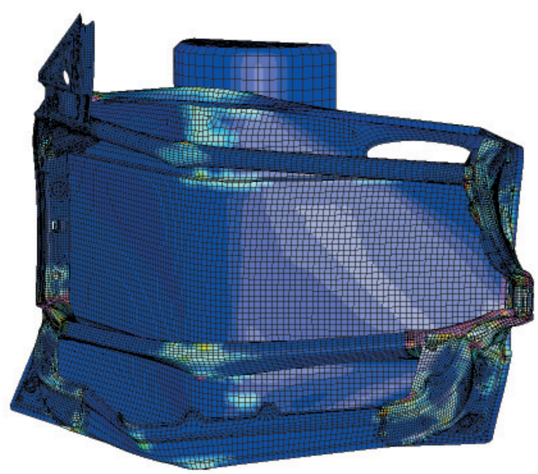
Both linear and non-linear analyses was utilized. The linear analysis used NASTRAN to consider the following load cases:

- Static Door Stiffness
- Dynamic Door Stiffness
- Vertical sag stiffness
- Upper lateral stiffness
- Lower lateral stiffness
- Normal modes

Non-linear analysis used LS-DYNA to perform quasi-static side intrusion and longitudinal door crush analyses. Quasi-static side intrusion is illustrated in Figure 12.

The Finite Element Model was developed with the modeling software, HyperMesh, and used in both linear and non-linear analyses.

Figure 12: **Quasi-Static Side Intrusion**



The CAE analysis results correlate in an acceptable range with the actual physical test results, except in the longitudinal door crush (see Figure 13) for which no physical test was conducted. The force/crush characteristics of the door structure in the longitudinal door crush analysis are shown in Figure 14. The graph shows the total force required to crush the door, as well as the forces carried by the outer panel, the lower beam and the upper beam. A total peak crush force of 60 kN and a sustained crush force of 20 kN are both sufficiently high to suggest that this door structure would make a considerable contribution to crash load management when tested in a full vehicle front impact event.

Figure 13: **Longitudinal Door Crush**

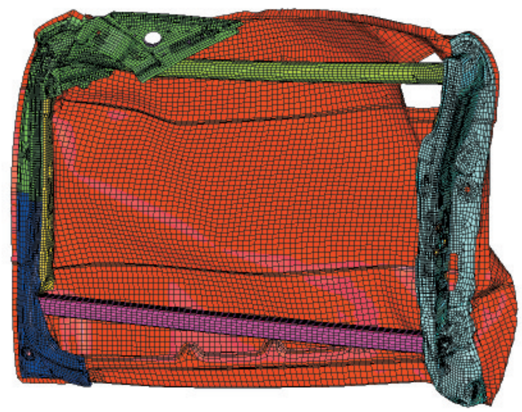
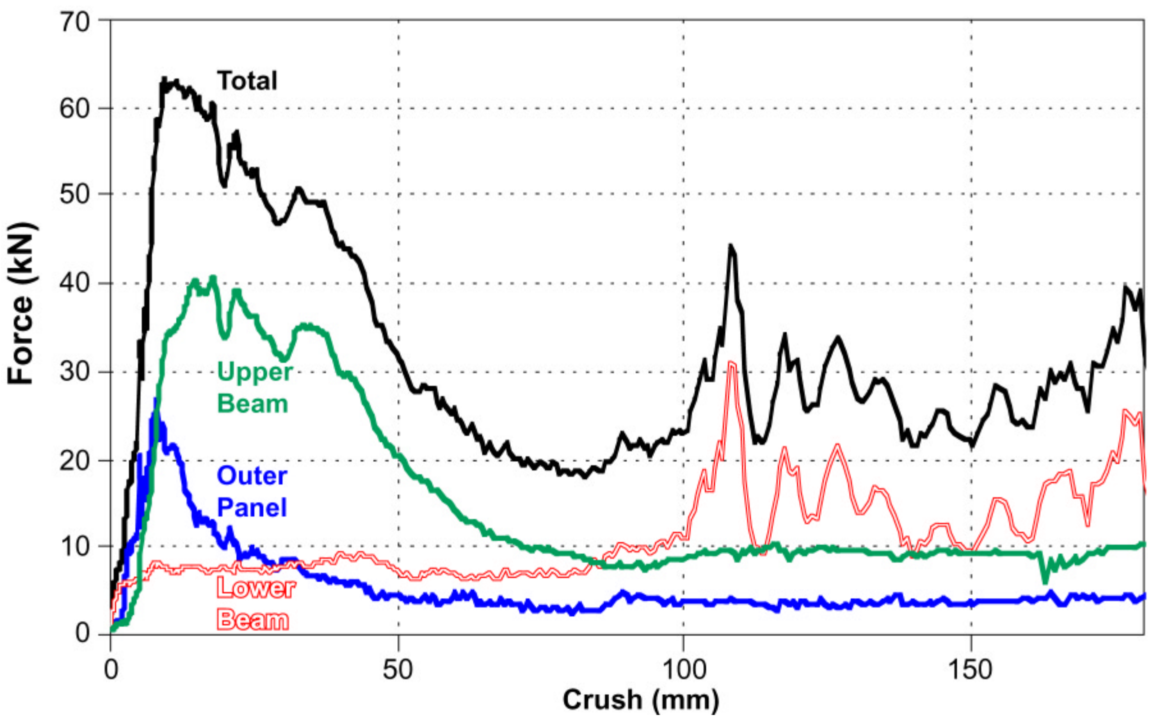


Figure 14: **Longitudinal Door Crush**



The ULSAC Consortium member companies provided all material-specific data and all materials used in manufacture.

6.1 Material Selection

As the frameless door design evolved during the Validation Phase, materials originally selected in the Concept Phase were reviewed again in terms of mass, performance and safety in a continued effort to make optimal use of steel's best attributes. Most crucial was the program requirement that the door be manufacturable in high volume using steels that are currently available.

Consequently, the ULSAC frameless door includes grades and thicknesses of steel taken from normal steel mill production. But to demonstrate optimal mass, safety and performance results at affordable prices, the ULSAC door uses some steel materials that are not commonly applied to closure panels.

Table 4 lists the material mechanical properties for each part.

Table 4: **Material Mechanical Properties**

Part No.	Material	Material Thickness (mm)	Yield Strength (0.2% offset) (MPa)	Tensile Strength (MPa)	Elongation A 80 (%)	r-value	n-value	Coating
3000 Door Outer Panel – Stamped	BH260	0.70	250	380	34	1.20	0.17	GA
3000 Door Outer Panel – Sheet Hydroformed	DP600	0.60	360	611	28	0.80	0.21	EG
3004 Inner Rear	140	0.60	150	294	43	1.98	0.23	GI
3008 Inner Front (tailored blank)	140 140	1.02 1.23	174 177	308 301	48 50	2.40 2.40	0.21 0.20	GA GA
3010 Lower Tube	DP800	1.56	650	868	13	*	0.04	EG
3012 Hinge Tube	280	1.20	357	394	37	*	0.08	GI
3014 Latch Tube	IS280	0.97	273	361	41	*	0.19	EG
3016 Outer Belt Reinf.	DP800	0.96	848	999	11	*	0.05	GI
3020 Mirror Flag	140	1.02	154	291	52	1.72	0.23	GI
3030 Latch Reinf.	140	1.23	177	301	50	2.4	0.20	GA

* Tubes – No r-value available

6.1.1 High Strength and Ultra High Strength Steels

ULSAC includes high and ultra high strength steels for crash and structural performance at reduced mass. The ULSAC program defines high strength steels as those with yield strength from 210 through 550 MPa and ultra high strength steels as those with yield strength above 550 MPa. The following parts are noteworthy for their use of these steels:

#3000 Door Outer Panel **–** Six different materials at two different thicknesses (0.6 and 0.7 mm) were considered for use in the ULSAC frameless door outer panel design to explore each material's mass reduction and performance potential:

- Bake Hardenable (BH) 210 MPa
- Bake Hardenable (BH) 260 MPa
- Interstitial Free (IF) 260 MPa
- Isotropic (IS) 260 MPa
- Dual Phase (DP) 500 MPa
- Dual Phase (DP) 600 MPa

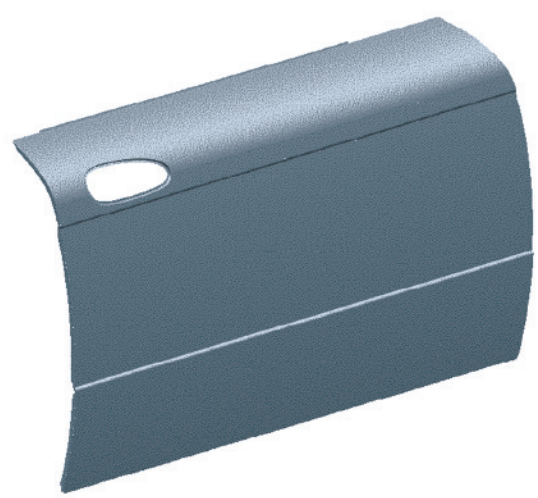
All six of these high strength steel grades were successfully manufactured, using conventional stamping techniques, into quality door outers, an important achievement considering the grades and thicknesses.

Three were ultimately selected for comparative dent testing: BH 210, BH 260 and DP 600, all in both 0.6 and 0.7 mm thicknesses. These three grades were selected because they represent a good range of steel grades for comparison purposes, and they are at the leading edge of steel material use in closure panels.

After completion of the dent testing on doors manufactured in each material grade and thickness, 0.7 mm BH 260 was selected as the material for the frameless door stamped outer panel. This selection was based on dent resistance and oil canning performance (see Figure 15).

In manufacturing test door structures with sheet hydroformed outers, a similar range of materials were used as those tested for dent resistance and oil canning in the manufacture of doors with stamped outers. Ultimately the Consortium chose 0.6 mm DP 600 steel to build demonstration hardware. This material was selected because it enabled above-average dent resistance and oil canning performance to be achieved as a result of the dual phase steel work hardening in the center of the particular panel, caused by the sheet hydroforming process.

Figure 15: **Door Outer Panel**



#3010 Lower Tube and #3016 Outer Belt Reinforcement – Both the lower tube and outer belt reinforcement use Dual Phase ultra high strength steel. Each was selected for ULSAC for its unique combination of properties and its purpose within the structural system. However, the steel used in the outer belt reinforcement is produced using a different galvanizing process (hot dip galvanized-GI) than that used in the lower tube (electrogalvanized-EG), which required a different chemistry to achieve the desired characteristics.

Dual Phase steel grades are medium alloy steels that provide superior formability for part manufacture. These steels work-harden significantly during forming to produce higher strength in the finished part. They are thus well suited for use where high component strength is required combined with the need to absorb deformation energy in the event of a crash. These two characteristics are of equal importance to ensure the integrity of the passenger compartment. Consequently, Dual Phase steels are an excellent choice for these two components which significantly affect the structural and crash performance.

For example, in a frontal collision, these two parts supply excellent load-carrying capabilities between the A- and B-Pillars. In a side crash, they provide the strength and absorption capabilities to efficiently manage impact energy forces.

#3012 Hinge and #3014 Latch Tubes – These parts are high strength hydroformed tubes, a process chosen for its advantages of high strength and excellent part formation at minimum weight. The complex shapes of the tubes facilitate attachment to the outer belt reinforcement and the lower tube, which creates a strong structural node. The tube hydroforming process is discussed in Section 6.2.2.

6.2 Processes

6.2.1 Tailored Blanks

Tailored blanks consist of two or more pieces of sheet steel with different material thicknesses, grades and/or coatings, joined by laser or mash seam welding.

Tailored blanks enable the design engineer to accurately situate the steel within the part precisely where its attributes are most needed. This leads to mass reduction because it allows for removal of mass that does not contribute to performance – using the right material for the right job.

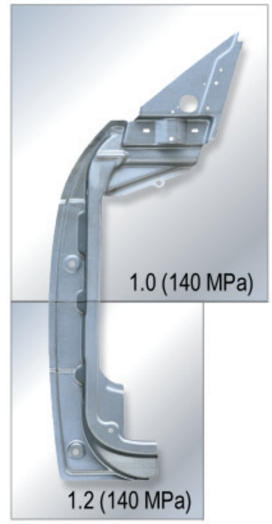
Steel's attributes strongly support the use of this technology, making it the only material currently delivering the benefits of tailored blanks in high volume manufacture.

Tailored blanks achieve:

- Increased vehicle safety through improved structural performance
- Reduced weight
- Reduced part count
- Reduced material and assembly costs

The ULSAC frameless door inner front uses a tailored blank. Results from the CAE analysis for structural performance determined the placement of steel in the ULSAC door inner front to provide extra hinge support. Figure 16 shows the blank layout.

Figure 16: **Blank Layout**



6.2.2 Tube Hydroforming

Tube hydroforming is gaining increasing acceptance in the automotive industry for a wide variety of components. Current applications include suspension frames, body structures, powertrain components and exhaust tubes.

In ULSAC, hydroforming is used to produce the latch and hinge tubes, adding stability to the door structure and allowing for integration of additional functions, such as the hinge attachment, latch attachment, and bushings.

Hydroforming provides several advantages versus stamped and welded structures, including:

- Reduced mass
- Reduced tooling costs
- Part integration and reduced part costs
- Integration of piercing and/or punching operations
- Elimination of pinch weld flanges
- Improvements to dimensional repeatability

When used with high strength steels, hydroforming produces structurally superior parts with thinner sections at reduced mass.

Though both the hinge and latch tubes were manufactured with similar hydroforming process steps, the latch tube's smaller wall thickness and three-dimensional curves made it a more complicated part to manufacture. The latch tubes part making process incorporates four steps:

1) Tube Manufacturing – The latch tube is made of 280 MPa yield strength high strength steel, using typical welding processes, such as high frequency and laser welding (see Figure 17).

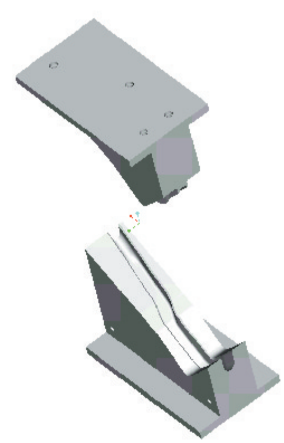
Figure 17: **Straight Tube**

2) Pre-bending – Due to the three-dimensional curves of the latch tube, the straight tube must be pre-bent. ULSAC used a conventional mandrel-bending machine for this step (see Figure 18).

Figure 18: **Mandrel-Bending Machine**

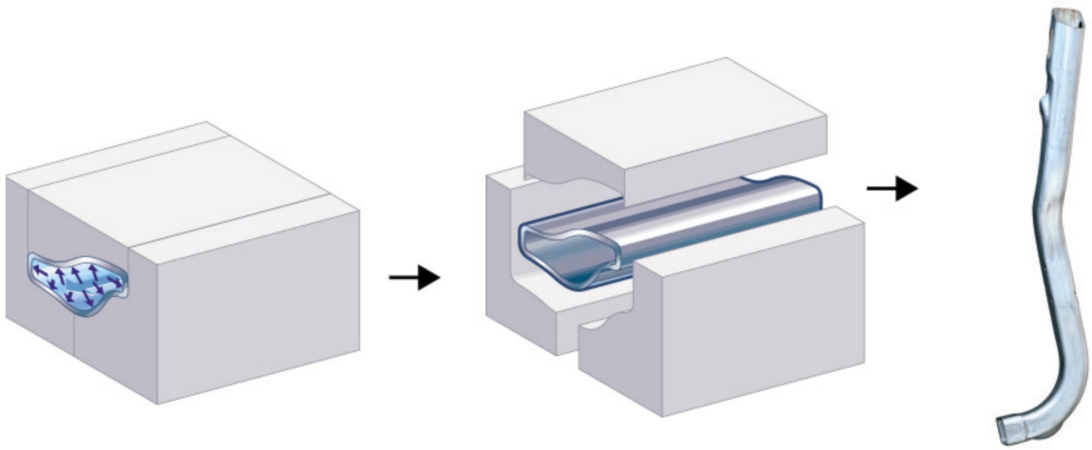
3) Pre-forming – Pre-forming is necessary to achieve proper initial start geometry that fits into the hydroforming tool (see Figure 19).

Figure 19: **Pre-forming Tool**



4) Hydroforming - The pre-formed tube is placed in the closed cavity of a forming die. Once the ends of the tube are sealed, the tube is filled and pressurized with a hydraulic fluid (1500 bar for the latch tube), forcing the tube into the shape of the tool cavity. Axial force at the tube ends feeds material into the cavity during forming, enabling formation of complicated shapes (see Figure 20).

Figure 20: **Hydroforming Process**



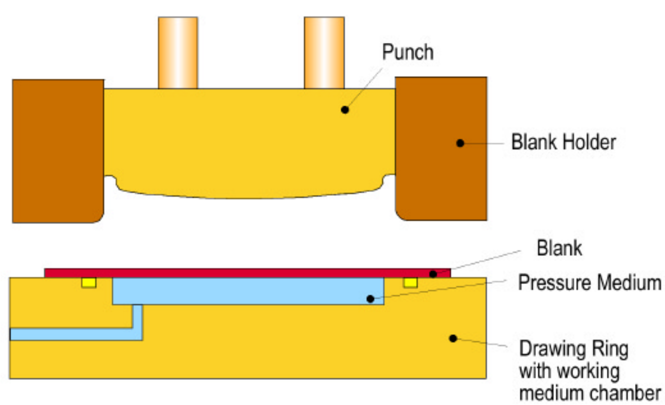
6.2.3 Sheet Hydroforming

Hoods, roofs and outer panels produced by conventional forming methods often lack sufficient stretch in the center of the part, which results in insufficient work hardening effects. So material thickness has to be increased to improve performance. However, increasing material thickness, of course, adds mass. The ULSAC program explored sheet hydroforming as a possible alternative to reduce this effect.

ULSAC utilized the active hydromechanical sheet metal forming (AHM) process. The AHM process is a multi-stage forming technology with a liquid working medium. The process environment consists of a forming press, process control, a pressure intensifier, and a forming tool. For ULSAC, the AHM process also included a Polyurethane (PU) calibration tool, which is described below under "AHM Process Tool Development."

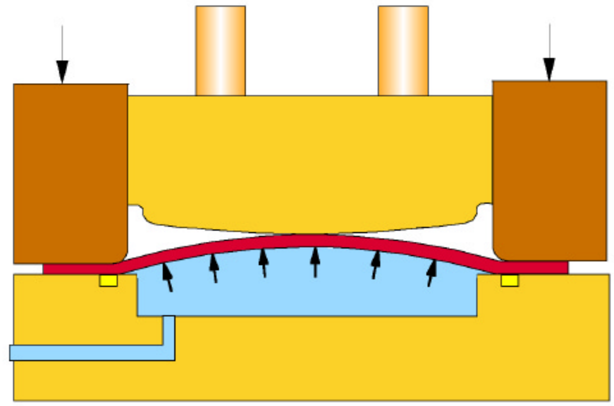
The die consists of three main components: a drawing ring, which is designed as a working medium chamber, the blankholder (binder) and the drawing punch. In the first stage the die is open and the flat steel sheet is loaded into the drawing ring (see Figure 21).

Figure 21: **Loading of Steel Blank**



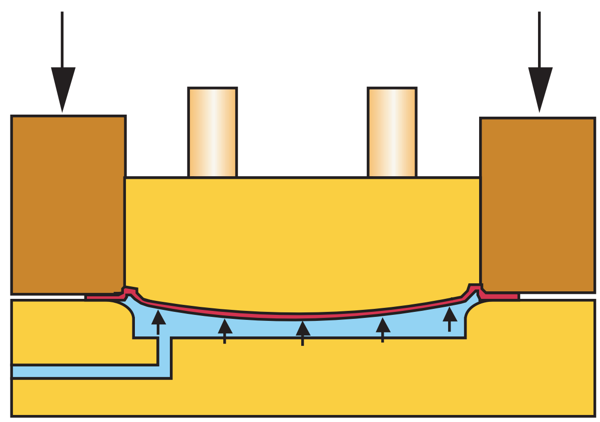
In the second stage, the die is closed and a pressure intensifier generates preforming pressure in the working medium chamber. This preforming process applies the first marks of the die on the prestretched blank (see Figure 22).

Figure 22: **Preforming Process**



The third stage is the reverse drawing process where the punch is lowered and preformed material is pushed in the opposite direction into the working medium chamber. With this reverse motion, the first contours of the outer panel are formed (see Figure 23).

Figure 23: **Reverse Drawing**



The final stage closely forms the part to its final shape. All press parameters and details of this process for ULSAC can be found in the January 2001 ULSAC Engineering Report (see Figure 24).

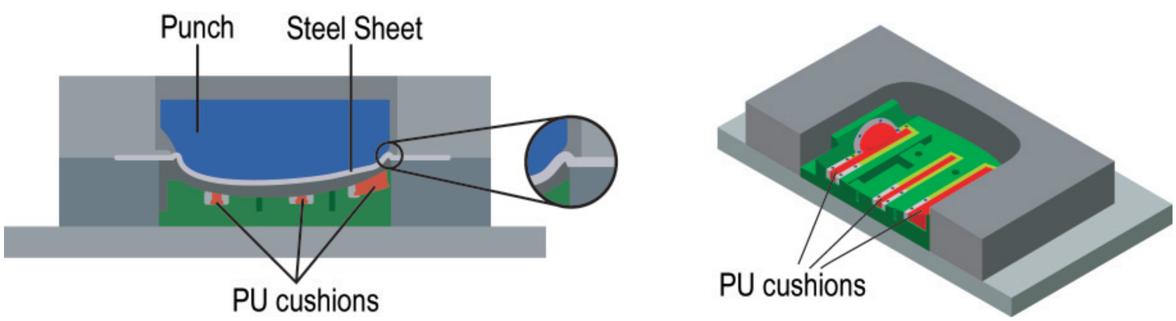
Figure 24: **Finished Part**

AHM Process Tooling Development **–** In press tryouts it was determined that higher pressures than those predicted by forming simulations were required to form the panel. After several tryouts, the press environment was modified to reach a higher working medium pressure in the range of 300 bar. The working medium chamber was redesigned and updated to resist the increased pressure. In addition, the press was modified with new ports and hoses to resist the higher pressure.

The combination of high strength steel materials and small radii, as specified in the parts design, requires a high working medium pressure to form the part to its final shape. In the case of the 0.6 mm DP 600 steel with a minimum radius of 3 mm, the required pressure is calculated to be approximately 700 bar. Calculations indicated a required press force of greater than 10,000 tons for this material, which would necessitate a press size that would not be economical for manufacturing outer panels.

Consequently a polyurethane (PU) insert was developed as an alternative solution to the use of a much larger press. The AHM process was combined with a calibration/ stamping process using PU-drawing cushions, eliminating the need for high calibration pressure to form the small radii in this part (see Figure 25).

Figure 25: **PU Calibration Tool with Calibration Inserts**

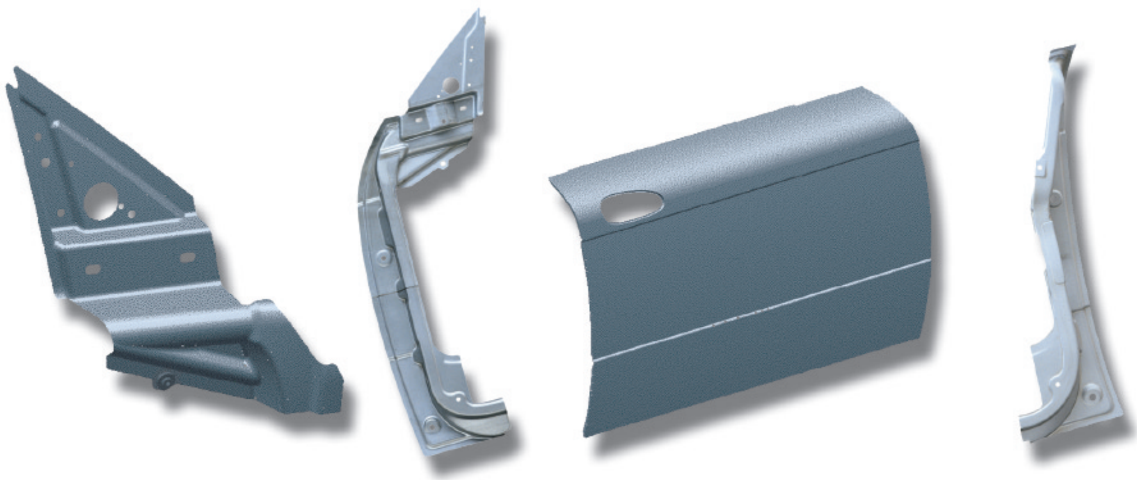


Using the combined hydromechanical manufacturing process, the required press force was reduced to 3,000-5,000 tons, thus enabling the use of a smaller press.

The AHM process requires longer press cycle times than that for conventional stamping. During this project, the AHM press manufacturer defined a press cycle time of 30 seconds for a 3000-ton press that would produce ULSAC door outers.

6.2.4 Stamping

Stamping is the most common manufacturing process for making structural parts in the automotive industry. The door outer panel, inner front, mirror flag, inner rear, and latch reinforcement are stamped parts. The inner rear stamping is very thin (0.6 mm) providing structural strength at reduced mass. An extension on the door inner front combined with a stamped panel mirror flag outer form a two-piece mirror flag. This design allows for the outer belt reinforcement to be sandwiched between the two parts, creating a strong and rigid structural node.



Forming Simulations

PES performed stamping and tubular hydroforming simulations, which generally are used to assess feasibility in respect to material thinning, material strain conditions and wrinkling that would exceed forming limit constraints. For ULSAC, the simulations were conducted in parallel with tool development to document a basis for series volume production feasibility.

Stamping simulation (see Figure 26) and circle grid analysis were conducted on the inner front and rear, mirror flag and door outer panel parts. In all cases, simulations correlated with the actual manufactured parts.

For the latch and hinge tube hydroformed parts, two different types of simulations were conducted: incremental (see Figure 27) and one-step. The forming simulation correlated with actual parts and indicates that simulation, particularly incremental simulation, can be a useful predictive tool for future development of tube hydroformed parts.

Figure 26: **Stamping Simulation**

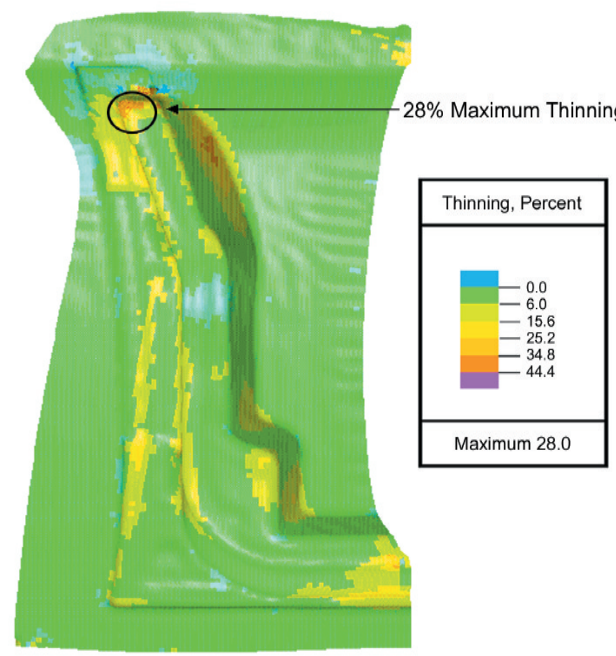
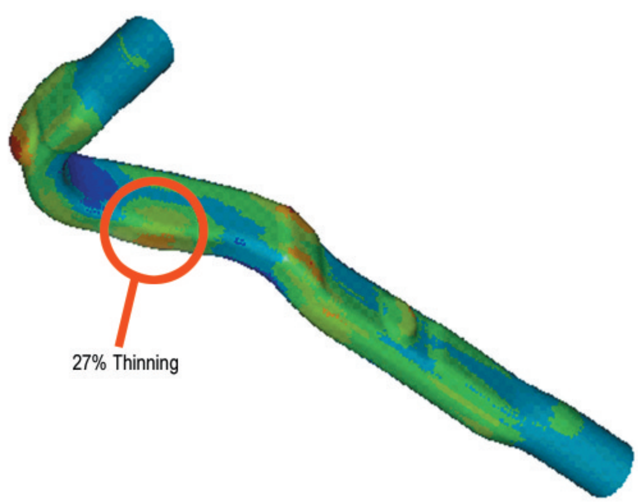


Figure 27: **Incremental Simulation**



To simulate the sheet hydroforming process manufacture of door outer panels, the incremental forming simulation AutoForm™ program was used and helped predict plastic strain, material thining and material failure in areas that were influenced by the reverse drawing step. In general, forming simulation indicated that the outer panel part could be manufactured with each of the steel grades and thickness using the sheet hydroforming process. However, the prediction of plastic strains in the outer panel middle section caused by the working medium pressure was not accurate.

8.1 Parts Manufacturing

Suppliers of manufactured parts were selected based on a set of criteria established by PES, the most important of which was the manufacturer's experience in producing production intent prototypes. Another was their proximity to Porsche AG's Weissach, Germany, facility where the doors were finally assembled.

The ULSAC program used simultaneous engineering to design and manufacture the parts for the frameless door. Simultaneous engineering, involving PES, part suppliers, assembly specialists, and material experts, initiates an efficient process of implementing changes to tool designs prior to their release for manufacture. It also ensures that all parts are manufactured successfully in a timely manner by addressing all issues of formability, spring back, tolerance control and assembly.

To prove manufacturing feasibility, the Consortium specified production intent standards for all parts, requiring that all parts be manufactured from tools with no manual forming. All stamping tools in this program were soft tools. Tooling optimization enabled stamping of quality door outer panels in six different material grades. Due to the need to withstand high forming pressures, hydroforming was accomplished using hard tools. In all cases, part fabrication tolerances and quality standards were maintained as if for full volume production.

During part manufacturing, PES coordinated material supply and gathered circle grid strain analysis data to compare with forming simulation results, confirming that the parts were formed to full volume manufacturing standards.

For tube hydroformed parts, comparison was made by first defining typical sections on the hydroformed component. Then the component was cut into sections to measure thinning and thickening.

To evaluate actual strain in the center of the sheet hydroformed door outer panels, 100 mm diameter circles were applied to three different areas of the panels (see Figure 28). Compared to the 0.7 mm BH210 and 260 materials, the strain analysis of the 0.6 mm DP 600 material indicates much higher values of plastic strain. These values were also much higher than those calculated by forming simulation. As noted previously, it was determined that the AutoForm™ software was not accurate enough to predict plastic strains in the middle of the ULSAC outer panel.

Figure 28: **Circle Grid Placement – Sheet Hydroforming**

Complete information to support part manufacturing feasibility was documented and includes material characteristics, press conditions, forming limit diagrams, process sheets and tolerance measurements.

8.2 Assembly

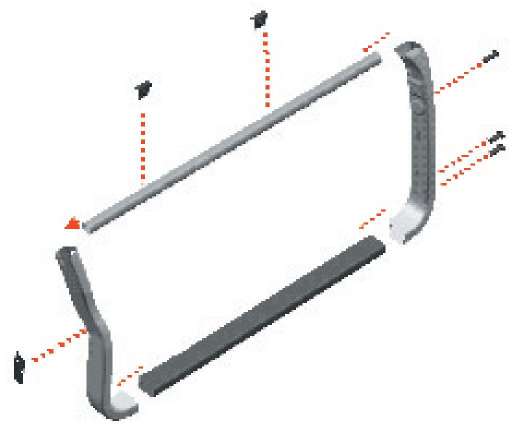
Assembly fixtures were developed, using CATIA™, in which the door parts could be adapted to a virtual fixture system. This enabled design of the complete fixture system as it was planned for actual assembly and subsequent try-outs of the assembly process. This virtual assembly simulation helped reduce the number of assembly fixtures for door manufacture through consolidation of multiple assembly steps into one fixture. Consequently, the ULSAC assembly time and cost were reduced. A final assembly sequence is provided in a computer-animated virtual assembly simulation in the April 2000 ULSAC Engineering Report.

8.2.1 Door Structure Assembly

Assembly requires joining the following subassemblies:

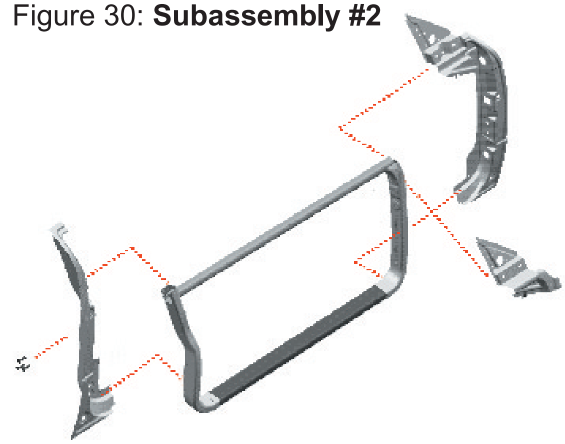
Subassembly #1 **–** Joining of tubular parts (see Figure 29): Hinge tube, latch tube, outer belt reinforcement, lower tube, hinge bushings, regulator attachment brackets and latch reinforcement. The hinge and latch tubes, outer belt reinforcement and regulator attachment brackets are joined using MIG welding. The two window regulator brackets are made of mild steel and assembled with clinch nuts. The hinge bushings use a combination of laser and MIG welding. Laser welding joins the latch reinforcement to the latch tube.

Figure 29: **Subassembly #1**



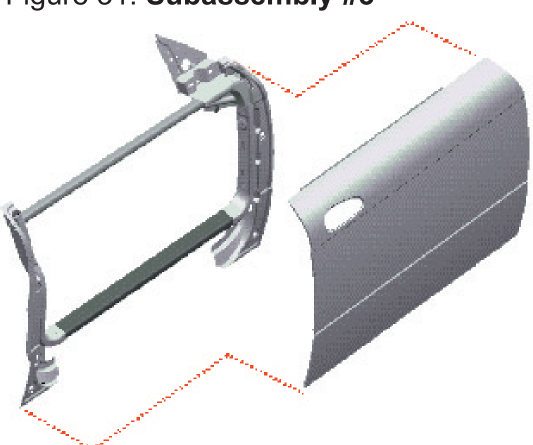
Subassembly #2 **–** Joining of this structure with front door inner parts (see Figure 30): Door inner front, inner rear, mirror flag outer and latch bushings. Laser welding joins the door inner front and inner rear to the hinge and latch tube, respectively. The mirror flag outer is joined to the inner front with spot welds and laser welded to the outer belt reinforcement. As with the hinge bushings, a combination of MIG and laser welding join the latch bushings to the latch tube.

Figure 30: **Subassembly #2**



Subassembly #3 **–** Bonding and hem flanging of door outer panel with Subassembly #2 (see Figure 31): The door outer panel is hem flanged to Subassembly #2 with an epoxy-bonding agent. Spot welds join the door outer panel lower inside overlap with the inner front and rear.
A self-sealing, plastic adhesive material, which expands under heat influence, bonds the lower tube to the outer panel for acoustic damping and stability.

Figure 31: **Subassembly #3**



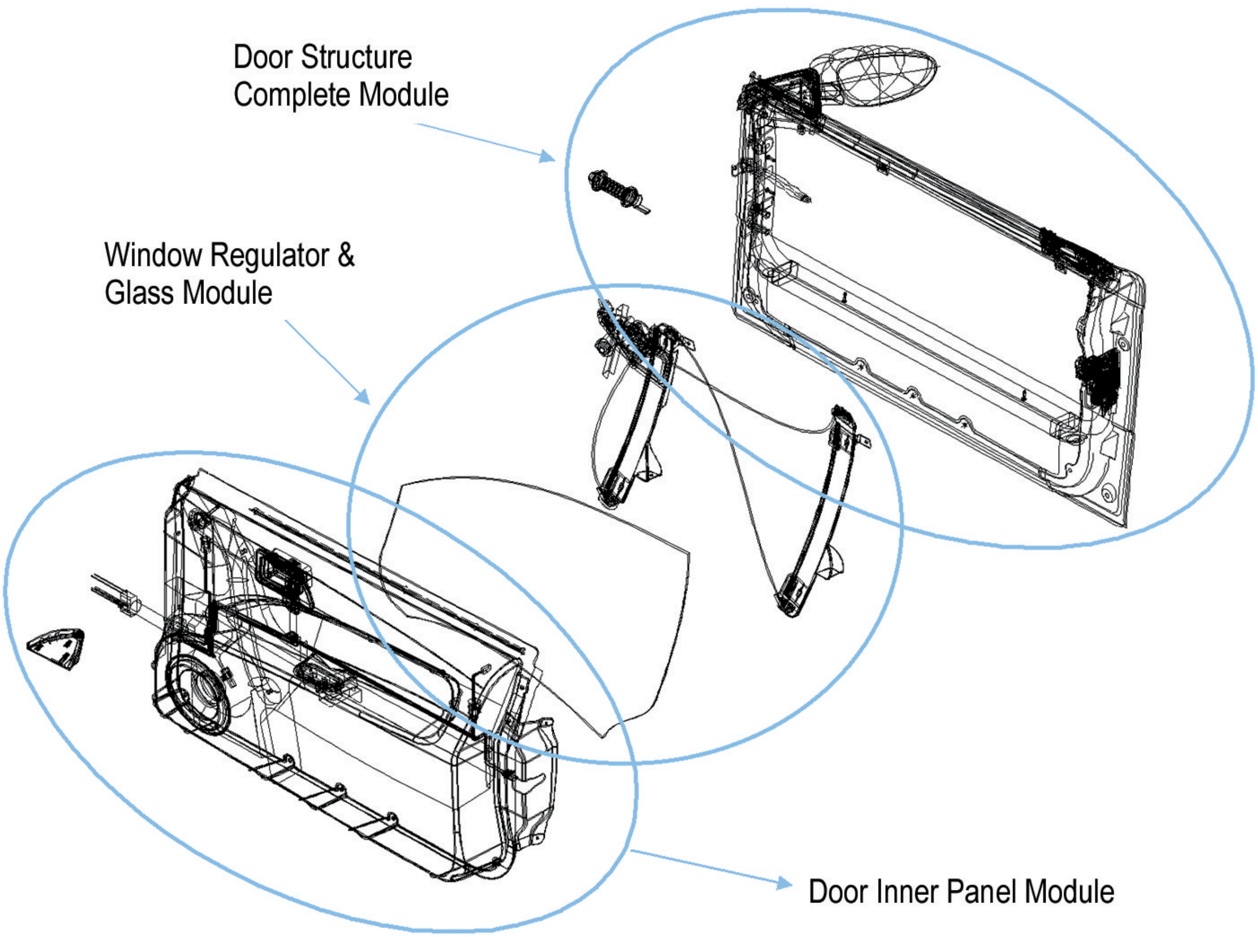
8.2.2 Door Complete Assembly

To assemble the door complete, the components package concept discussed in Section 4.2 is incorporated in three subassembly modules as shown in Figure 32 and fitted to the painted door structure. Following is the package component assembly sequence:

Door Structure Complete Module –
The following components comprise this subassembly:

- Outside remote handle
- Door latch
- Mirror
- Check strap
- Outer belt seal
- Mirror flag seal
- Boot harness

Figure 32: **Assembly Sequence with Main Assemblies**



Window Regulator and Glass Module – (see Figure 33). The window regulator module is mounted and the glass attached.

Door Inner Panel Module – The vapor barrier and inner trim panel module are attached to create the final door complete (see Figure 34).

Figure 33: **Window Regulator**

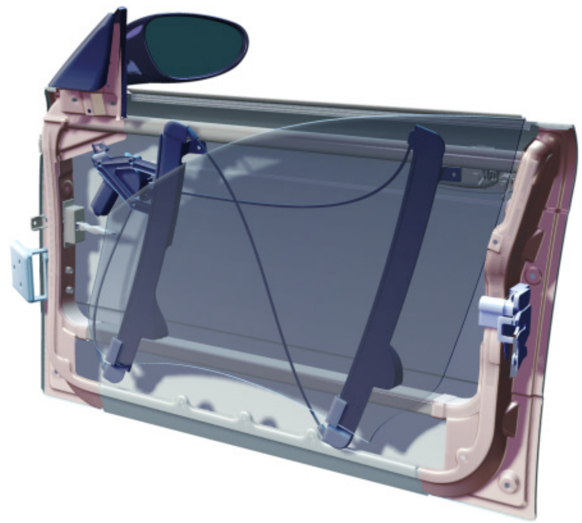
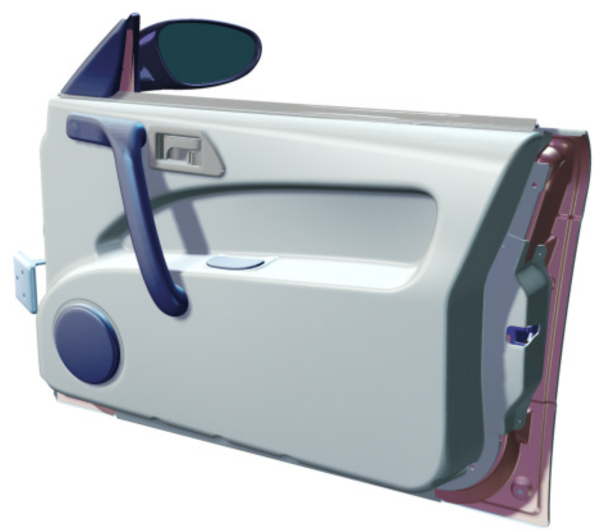


Figure 34: **Door Complete**



9 Testing and Results

In the ULSAC Validation Phase, structural testing of the ULSAC door was conducted to confirm structural performance, and additionally, dent resistance and oil canning testing were conducted to select the most suitable outer panel material/thickness for the ULSAC demonstration hardware.

The intent of the dent resistance and oil canning testing was to investigate the effect of steel type and thickness and thus, the mass of the outer panel. The test results confirmed that high-quality dent resistance and oil canning performance can be achieved with the use of high strength steels at reduced material thickness. Structural testing confirmed state-of-the-art performance for today's frameless doors.

9.1 Mass Results

The ULSAC frameless door with stamped outer panel weighs just 10.47 kg. This is 1.76 kg below the target mass of 12.23 kg, as specified in the ULSAC Concept Phase.

To compare these mass results with benchmarked frameless doors, the masses of all doors were normalized as the ratio of door structure mass to the true outer surface area, taking surface curvature into account (kg/m^2), a procedure carried over from the Concept Phase.

In the Concept Phase, a wide range of doors were benchmarked, with the best-in-class being a framed door with a normalized mass of 17.01 kg/m^2. To compare the frameless door design chosen for validation, PES benchmarked three additional frameless doors during the Validation Phase to enable a more precise comparison to the the ULSAC door. The ULSAC door with stamped outer panel is 22 percent lighter than the framed door best-in-class benchmark; and 42 percent lighter than the average frameless door Validation Phase benchmark.

Utilizing a 0.6 mm DP 600 sheet hydroformed outer panel manufactured with the AHM process proved to reduce the overall mass further, performing better than the target by 2.46 kg. (The assembled door structure with the 0.6 mm nominal thickness sheet hydroformed outer panel weighed 9.68 kg. However, in the economic analysis, a calculated mass of 9.77 kg. was used to determine manufacturing cost. To be conservative, and in keeping with the slight changes in weight which can be expected in a manufacturing environment, the calculated mass of 9.77 kg has been used to compare to the ULSAC targets and benchmarks.) Evaluation of this developmental process indicates that there is the potential for additional weight reduction with a sheet hydroformed outer panel, achieving 27 percent savings over the best-in-class benchmarked door and 46 percent over the average frameless door benchmark. These details are shown in Table 5.

Table 5: **ULSAC Benchmarking and Comparison Data**

	Normalized Mass (kg/m²)	Mass Door Structure (kg)	True Surface (m²)
ULSAC Validation Phase - Stamped Outer Panels	13.27	10.47	0.789
ULSAC Validation Phase - Sheet Hydroformed Outer Panels	12.38	9.77	0.789
ULSAC Concept Phase Target	15.50	12.23	0.789
Framed Best In Class Concept Phase	17.01	13.42	0.789
Door A	24.94	16.14	0.647
Door B	19.76	15.55	0.787
Door C	24.36	21.68	0.890
Avg. Benchmark Validation Phase	23.02		
Avg. Benchmark Concept Phase	19.74		

Figure 35: **Results Summary**

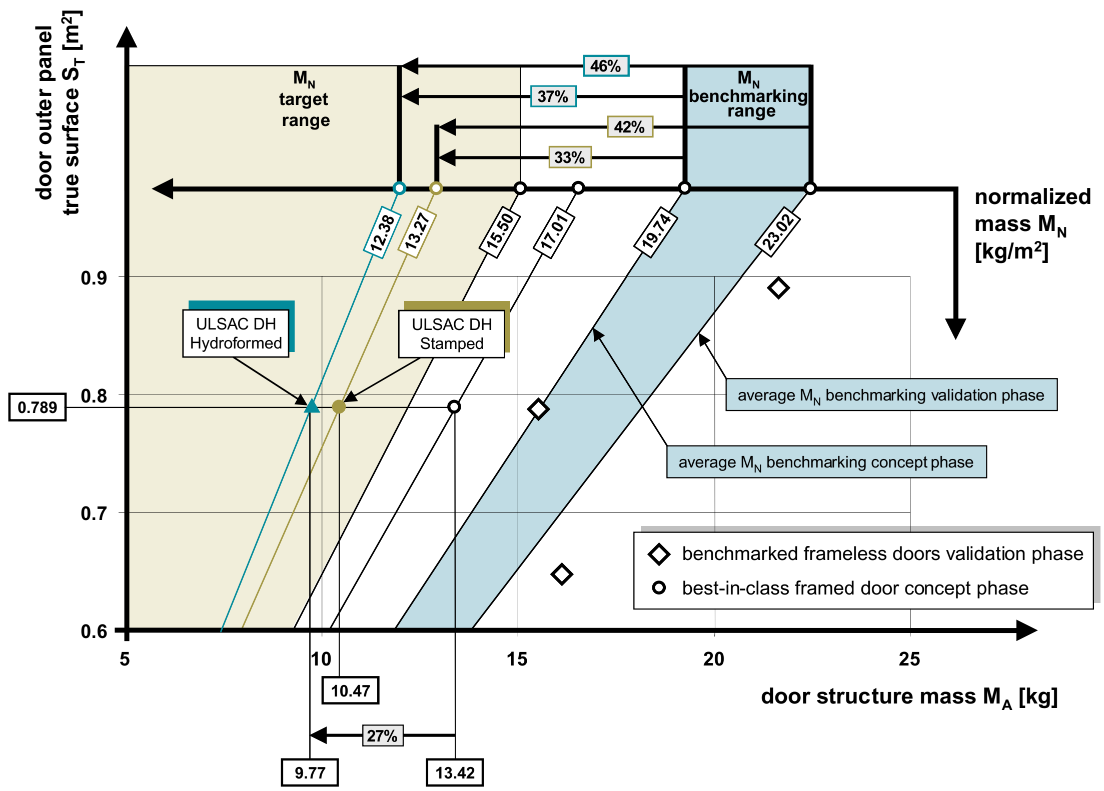


Figure 35 summarizes these impressive results. The ULSAC frameless door combines this lightweight design with comparable or improved dent resistance, oil canning and structural performance, as described in Section 9.2.

9.2 Dent Resistance and Oil Canning

The ULSAC doors underwent laboratory tests that measure resistance to typical impacts to which auto bodies are subjected. Four dent tests were used:

Quasi-static incremental **–** The quasi-static test applies force at 50 mm per second (mm/s) (equal to 0.18 km/h) at successive loads, while measuring the dent depth result from each load increment. This standardized test, known as the Auto/Steel Partnership Standardized Dent Test is used to evaluate the relative dent resistance of different materials in a given panel design.

Dynamic incremental **–** This test is designed to simulate the impact caused by a rolling shopping cart or a door-to-door impact; the load is applied at an impact speed of 250 mm/s equal to 0.9 km/h. Measurement of dent resistance uses same process as in the quasi-static test.

Dynamic high speed (Two types) **–** Two different types of dynamic tests were used to measure high speed dynamic dent resistance capabilities. Lab 1a represents the force of a stone chip. Lab 1b simulates the force of a hailstone. Separate facilities conducted the tests on assembled doors, using similar air gun-like testers, which fire a steel ball at the door. The shape and depth of indentation in longitudinal and transverse directions are measured to determine test results.

The quasi-static results revealed that the dent resistance of the hydroformed door panels is quite similar to dent resistance of the stamped doors. The dynamic dent resistance results show the same behavior and ranking as the quasi-static results with slightly improved values due to the positive strain rate sensitivity of steel.

All of the hydroformed outer panels were thinner than their stamped counterparts, yet displayed essentially the same dent resistance because of the increased work hardening that occurred during hydroforming.

The 0.7 mm BH 260 selected for stamped outers was tested with galvannealed (GA) coating. The 0.6 mm DP 600 selected for sheet hydroformed outers was tested with both hot dip galvanized (GI) and electrogalvanized (EG) coatings. Dent resistance results are shown in Figures 36-39 following:

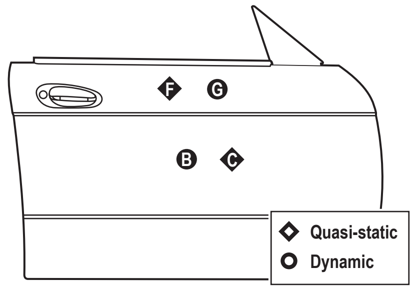


Figure 36: **Quasi-Static Incremental – Critical Dent Load for 0.1 mm Dent**

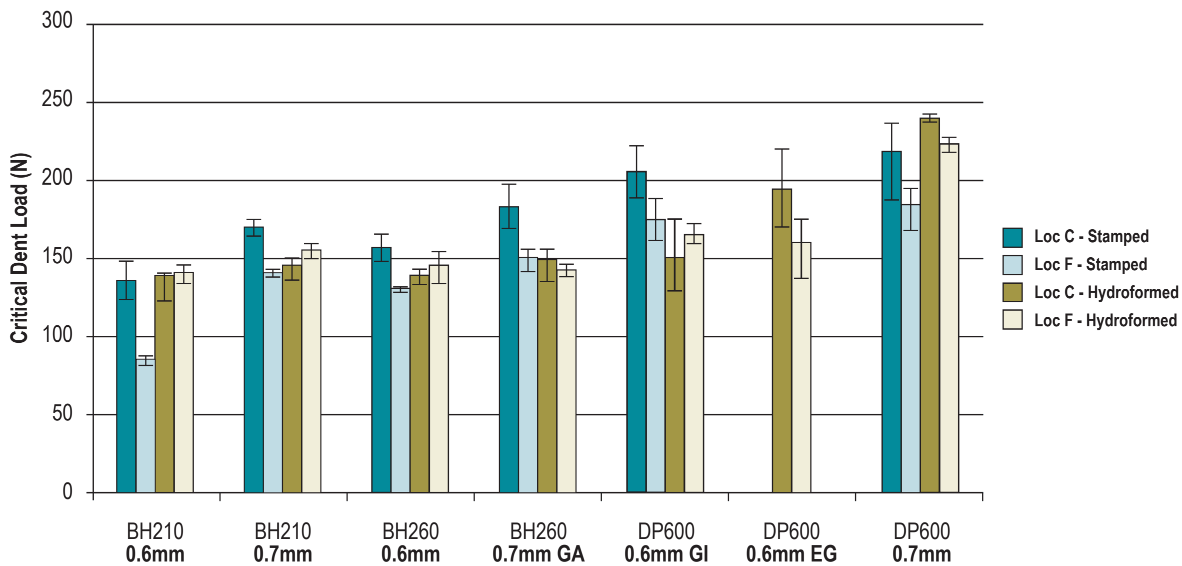
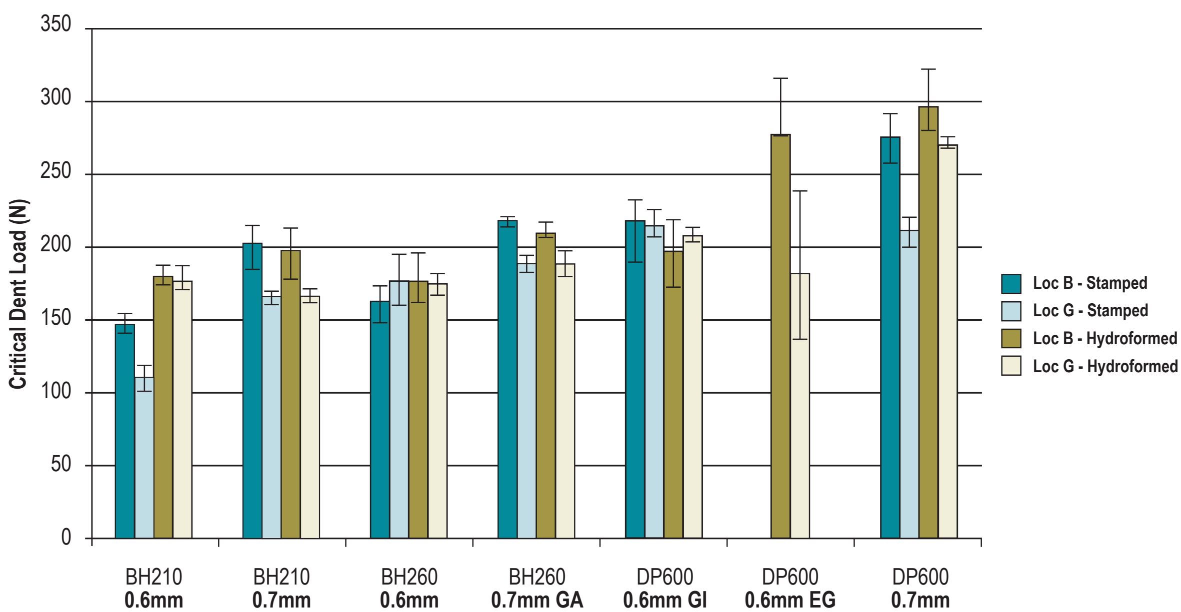


Figure 37: **Dynamic Incremental – Critical Dent Load for 0.1 mm Dent**



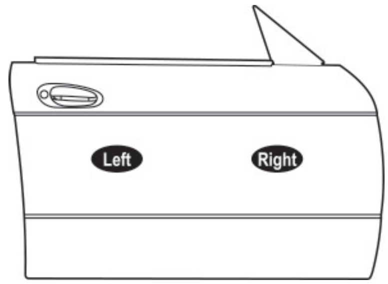


Figure 38: **Lab 1a – Dynamic High Speed – Dent Depth (6 mm, 0.88 g bullet)**

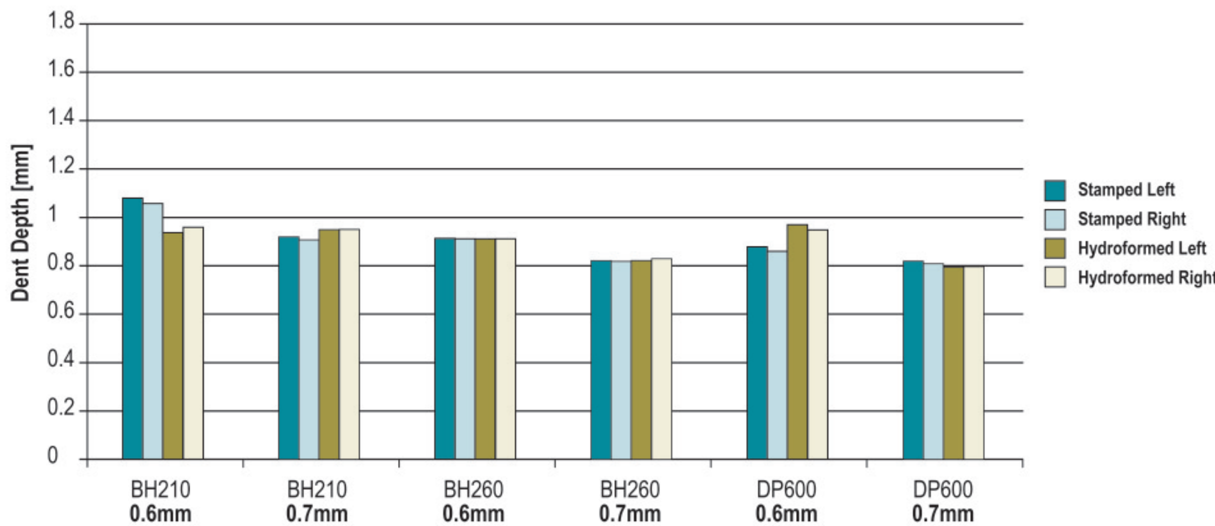
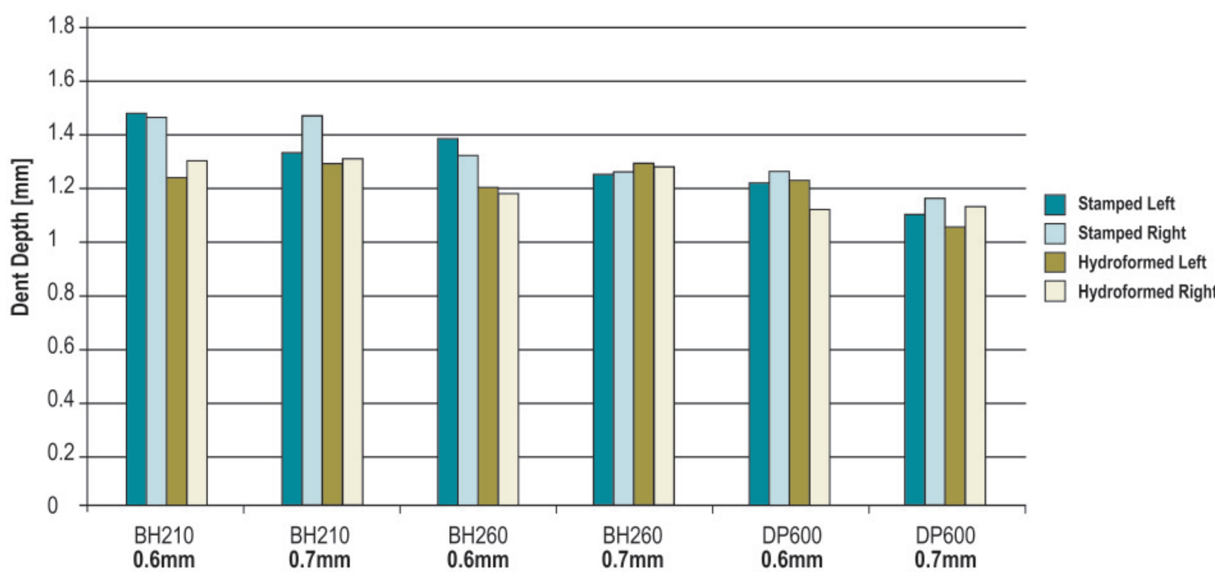


Figure 39: **Lab 1b – Dynamic High Speed – Dent Depth (18 mm, 23.8 g bullet)**



The ULSAC door also was evaluated for oil canning. The door with stamped outer panel made of 0.7 mm BH 260 steel exhibited slight oil canning in the mid region, which would meet current expectations. With minor design alterations or the addition of a molding, oil canning could improve.

Oil canning performance in the test doors with hydroformed outer panels differed significantly from the behavior of those with stamped doors. Occurrences of oil canning found in some of the stamped test doors were improved with the hydroformed doors on all materials tested, although the centers of all hydroformed doors showed lower stiffness than their stamped counterparts. This is related to the fact that thickness is the dominant factor for stiffness for a given part, design and material combination. Therefore, material thinning, which naturally coincides with material stretching, may lead to a loss of stiffness. With regard to dent resistance, this loss in thickness may be overcome by the increase of strength due to work hardening.

Since the 0.6 mm DP600 steel shows above average performance in oil canning and has met the requirements for static and dynamic dent resistance, this material was chosen for the door structures with sheet hydroformed outer panels.

9.3 Upper and Lower Lateral Stiffness

To measure the upper lateral stiffness, the door is restrained at the lock and hinges and force applied to upper rear outer corner. In the lower lateral stiffness test, force is applied to the lower rear outer corner. Deflection is measured with a displacement transducer.

ULSAC doors exhibit state-of-the-art lateral stiffness compared to the benchmarked frameless doors, at greatly reduced mass. Results of the tests confirmed the structural performance of the door design is not sensitive to the door outer material thickness in the tested range, as indicated in Table 6.

Table 6: **Upper and Lower Lateral Stiffness**

	Door A	Door B	Door C	ULSAC DH Stamped Outer Panel	ULSAC DH Sheet Hydroformed Outer Panel
Upper Torsion Nm/deg	352	197	188	245	242
Lower Torsion Nm/deg	467	309	188	250	203

9.4 Door Sag

To test ULSAC for door sag performance, the door is restrained at the hinges, and force is applied at the latch. The vertical downward deflection is measured with a displacement transducer.

Benchmarking of frameless doors shows that ULSAC doors, in respect to vertical door sag, perform similarly to doors currently in production at a significantly reduced mass (see Table 7). Again, the test confirmed that the affect of material thickness change in the tested range was negligible to door sag performance.

Table 7: **Door Sag**

	Door A	Door B	Door C	ULSAC DH Stamped Outer Panel	ULSAC DH Sheet Hydroformed Outer Panel
N/mm	109	199	497	157	181

9.5 Quasi-Static Intrusion

It is important to demonstrate that the low mass ULSAC frameless door structure can provide sufficient side intrusion protection. A quasi-static side instrusion test, similar to U.S. FMVSS 214, in which a door is tested in complete vehicles, was performed on the doors with stamped outer panels to test the structure for its safety. Since the door is not designed to fit any particular vehicle, a comparison with state-of-the-art frameless door benchmarks was made to assess the ULSAC performance.

To ensure a fair comparison, the benchmarked doors were also tested in the same manner as the ULSAC door. Since the benchmarked doors are currently part of production vehicles sold in the United States, they have been tested in a complete vehicle according to FMVSS 214 and have met the standard. It is assumed that by achieving similar results as the benchmarked doors, the ULSAC door will also meet the FMVSS 214 requirement if tested in a full vehicle.

Test Set Up **–** (see Figure 40)

- Door is mounted to a rigid test rig representing a rigid front hinge pillar and B-pillar. It is restrained at the hinges and latch, but is allowed to pivot at the hinges.

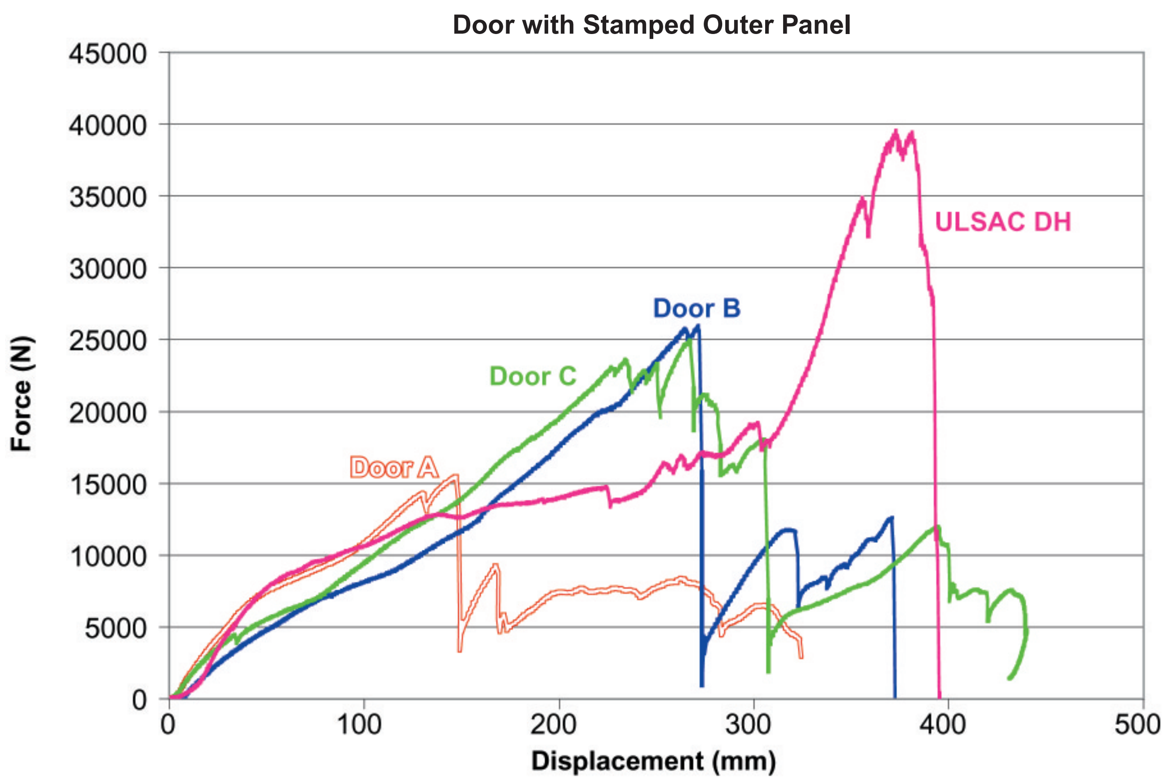
- A cylinder drives horizontally into the door at a rate of 127 mm/s, 0.0416 km/h for a total of 457 mm (18 inches) of displacement.

- Forces at 152 mm (6 inches), 305 mm (12 inches) and peak crush are recorded.

Figure 40: **Quasi-Static Intrusion Test Set Up**

The results of this test (see Figure 41) show that the ULSAC door performs better than the comparison doors. Therefore, it is reasonable to assume that when tested in a full vehicle, the ULSAC door will also meet the quasi-static requirements of FMVSS 214.

Figure 41: **Side Intrusion Force/Displacement**



Economic Analysis

A detailed economic analysis was performed to determine total manufacturing cost effectiveness, using an interactive process among product designers, stamping process engineers, assembly line designers and cost analysts.

10.1 Cost Model Development and Use

The economic analysis used a technical cost model program, which is a further development of the cost modeling approach used in the UltraLight Steel Auto Body (ULSAB) program.

In developing a cost model, the goal was to provide end users with the ability to use the ULSAC model to independently investigate various production scenarios and compare existing or potential door structures to the ULSAC door structure. Consequently the technical cost model has been programmed to allow users to change general inputs to suit their own specific production environment or to change specific inputs for alternative processes. In addition, because the costs shown on the ULSAC cost model reflect only direct factory costs and are relevant to the current level of product development, the model has been set up to accommodate entering of additional cost categories. The full electronic spreadsheet is included in the April 2000 ULSAC Engineering Report.

10.2 Analysis Overview

The ULSAC Economic Analysis began with the establishment of the basic assumptions regarding general inputs. The ULSAC Economic Analysis established the estimated production costs, based on typical automotive high volume production, against an extremely well defined design. Having a process design meant that costs could be analyzed based on exact definitions concerning fabrication and assembly requirements.

On the parts fabrication side, each stamping and hydroformed component was studied to determine the process. Stamping and hydroforming suppliers provided a proposal for the manufacturing process and the corresponding input data for the model.

In parallel, parts were analyzed to obtain corresponding manufacturing engineering input data. This data and the manufacturing proposals were compared to ensure reasonableness. Then input data used in the cost analysis was defined. For extremely small parts or parts which require no fabrication processes, such as stamping or hydroforming, it was assumed that these would be purchased.
To develop assembly line design and processing, suppliers were provided with a detailed bill of materials and parts sequencing. From this, the door assembly area was developed in a macro view, which established equipment, tooling, building and manpower required to fulfill the production requirements. Following validation of the data, it was then integrated into the cost model for final cost estimation.

Once ULSAC costs were determined with the model, a sensitivity analysis investigated potential cost movements with respect to labor wage, production life, equipment life, interest rate, unplanned downtown for stamping and material prices

From data gleaned through the benchmarking of three frameless state-of-the-art doors, a state-of-the-art generic door was developed and a cost analysis conducted with which to compare the ULSAC door.

10.3 Analysis Results

The results of the economic analysis (see Table 8), for doors manufactured in an annual production volume of 225,000, show that a door structure with vast weight savings and comparable performance to state-of-the-art generic doors can be manufactured in production volume at affordable costs.

ULSAC doors with stamped outer panels achieve a 42 percent weight reduction, yet cost no more than the state-of-the-art generic doors. The economic analysis of the outer panel using the sheet hydroforming process reveals that the costs are $3.72 higher than the cost of the similar conventional stamped panel, assuming an annual vehicle production volume of 225,000 units a year. For that increase in cost, a calculated 0.7 kg mass reduction for each door has been achieved.

Table 8: **Economic Analysis Results**

	Stamped Outer ULSAC LH&RH Door	**Sheet Hydroformed Outer ULSAC** LH&RH Door	**"State of the Art" Generic Door** LH&RH Door
Parts Fabrication	**$79**	**$86**	**$91**
Material	$28	$28	$48
Stamping	$15	$6	$16
Tailored Blank Stamping	$12	$12	$20
Tubular Hydroforming	$15	$15	$0
Purchased Parts	$9	$9	$7
Assembly	**$54**	**$54**	**$47**
Total Cost of Doors (2)	**$133**	**$140**	**$138**

Note – costs shown are for a set of two (2) doors

The material costs for the hydroformed outer panel compared to the stamped outer panel are almost identical. Higher costs for ultra-high strength steels are compensated by the thinner gauges and less steel weight applied. However, the cost differences are most noticeable in the higher labor and equipment costs associated with the AHM process. Additionally, labor costs, along with equipment costs, depend on the cycle time. AHM requires longer cycle times when compared to stamping. Tooling costs per part are reduced by the sheet hydroforming operation, but these savings are not enough to offset the overall higher costs of hydroforming in this program. Sheet hydroforming would be more cost competitive in lower manufacturing volume programs.